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The Global Surface Roughness of 433 Eros from the NEAR Laser Rangefinder

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Abstract

We performed the first global surface roughness assessment of the asteroid 433 Eros at baselines (horizontal distances) of 4–200 m. We measured surface roughness using the root-mean-square (RMS) deviation over a variety of baselines after first detrending the height to remove long-wavelength slope effects. The global surface roughness of Eros is found to be self-affine at all baselines investigated. The surface roughness is statistically correlated with crater density at baselines of 100–200 m and boulders at a baseline of 5 m. No global spatial statistical correlation was found for baselines of 4–200m and mapped tectonic lineaments, ponds, slope, or geopotential elevation. The surface roughness of the crater Shoemaker (Charlois Regio) is controlled by the interplay of a high boulder density producing higher surface roughness values at small baselines and low crater density lowering surface roughness values at long baselines. We estimated the mobile regolith thickness (regolith that moves around and infills topography) to be 0.2–6.2 m from the differ-

ence in the surface roughness values at the baseline of 4 m. Furthermore, we find that the change in RMS deviation as a function of baseline compares favorably with the moon, and differs significantly from existing results for rubble-pile asteroid Itokawa.

Keywords: Asteroids, Topography, 433 Eros, Boulders, Impact Craters

1. Introduction

Surface roughness is a statistical measure of the change in topography over a specified horizontal scale after removing a trend (Shepard et al., 2001). Studies of the surface roughness of asteroids can be divided into two classes based on the horizontal scale of surface roughness. The majority of asteroid studies focus on centimeter-scale surface roughness derived from radar studies (e.g. Benner et al., 2008) and thermal modeling (e.g., Harris and Lagerros, 2002). The other class of studies focuses on the surface roughness estimated at horizontal scales > 1 -meter using measured asteroid topography (Cheng et al., 2001, 2002; Abe et al., 2006; Barnouin-Jha et al., 2008). The latter studies use scales similar to those used for evaluating surface roughness on larger planetary bodies such as Mars, Moon, and Mercury (Garvin et al., 1999; Rosenberg et al., 2011; Kreslavsky et al., 2014) and permit statistical comparisons between asteroids and planetary bodies. Meter-scale surface roughness studies require accurate topography of asteroids with vertical resolutions that are at least a factor of 10 better than the horizontal scales over which the roughness is evaluated. Such high-quality topography is available from robotic missions to asteroids when they include laser altimeters (i.e., Near Earth Asteroid Mission, NEAR, Shoemaker to 433 Eros and Hayabusa

20 to 25143 Itokawa), or when they include extensive imaging with high spatial
21 resolutions. This study focuses on surface roughness measured at horizontal
22 scales ranging from 4–200 m on the asteroid 433 Eros (hereafter called Eros)
23 using the NEAR Laser Rangefinder (NLR) altimetric data.

24 Eros is a large elongate 30 x 15 x 15 km asteroid with a density of 2.67
25 ± 0.1 g/cm³ (Veverka et al., 2000), a porosity of 20–25 %, and is likely a
26 fractured shard (Wilkison et al., 2002). Previous studies of the surface rough-
27 ness of Eros measured the meter-scale surface roughness from individual NLR
28 tracks for specific regions across the asteroid (Cheng et al., 2001, 2002). The
29 highest surface roughness values were found within the 5 km-diameter crater
30 Psyche, specifically on Psyche’s rim and walls, where boulders are common.
31 Regions near the Rahe-Dorsum of Eros, a large fault with associated surface
32 lineaments, was also associated with higher surface roughness values.

33 The surface roughness of 25143 Itokawa for a few regions,(Abe et al.,
34 2006; Barnouin-Jha et al., 2008) was obtained from a laser altimeter using a
35 smaller range of horizontal baselines (5–100 m) than measured on Eros. 25143
36 Itokawa (hereafter called Itokawa) is a small elongated (0.55 x 0.3 x 0.25 km)
37 rubble-pile asteroid (Fujiwara et al., 2006) with two terrain types: lowlands
38 that have lower surface roughness values than Eros and highlands that have
39 similar surface roughness values to Eros (Abe et al., 2006; Barnouin-Jha et al.,
40 2008). The difference in surface roughness values between the two regions
41 is due to the higher density of boulders in the highlands. If, as imaging
42 suggests, (Miyamoto et al., 2007) the lowlands were previously covered in
43 boulders and were buried by regolith, the difference in surface roughness at
44 smaller baselines could provide a lower bound estimate of regolith thickness

45 on Itokawa. Using this methodology, Barnouin-Jha et al. (2008) found a
46 lower bound estimate of regolith thickness for Itokawa of 2.3 ± 0.4 m. In all
47 of the previous studies of the meter-scale surface roughness of asteroids the
48 topography was not detrended to remove pre-existing large-scale topography
49 before the surface roughness measurements were performed, although areas
50 on Itokawa were chosen to have low slopes (Abe et al., 2006; Barnouin-Jha
51 et al., 2008).

52 While these studies provide valuable insight into the surface properties
53 of Eros and Itokawa for specific regions none of them include a global as-
54 sessment of surface roughness as has been done for larger planetary bodies
55 (e.g., Kreslavsky and Head, 2000; Rosenberg et al., 2011). In this study,
56 we measure the global meter-scale surface roughness of Eros. Global surface
57 roughness maps can provide inferences on which geologic processes influence
58 regional topography to modify the asteroid’s surface roughness. Candidate
59 processes for Eros include impact cratering (e.g., Chapman et al., 2002), for-
60 mation of lineaments (e.g., Buczkowski et al., 2008), regolith processes and
61 boulder mobilization (e.g., Thomas et al., 2002), and the creation of ponds
62 (e.g., Robinson et al., 2001). Many of these processes have been cited as
63 key contributors to changes in surface roughness on other bodies including
64 cratering on the Moon (Rosenburg et al., 2011), and tectonics and cratering
65 on Mercury (Kreslavsky et al., 2014; Susorney et al., 2017).

66 We use root-mean-square, RMS, deviation (the RMS of the difference in
67 detrended height over a specified horizontal scale) as our measure of surface
68 roughness for several reasons. First, RMS deviation is widely used in surface
69 roughness investigations of asteroids using radar (e.g., Benner et al., 2008)

70 and thermal datasets (e.g., Harris and Lagerros, 2002). Additionally, RMS
 71 deviation has been used in previous investigations of the surface roughness
 72 of asteroids (Cheng et al., 2001; Barnouin-Jha et al., 2008) and in investiga-
 73 tions of larger planetary bodies (e.g., Rosenburg et al., 2011) allowing us to
 74 compare our data to previous studies. Second, RMS deviation is frequently
 75 used to model topography of a surface as a self-affine fractal if RMS devi-
 76 ation scales with a given length-scale (or baseline) as a power law with a
 77 constant exponent, known as the Hurst exponent [Turcotte, 1997]. A single
 78 diagnostic Hurst exponent [Shepard et al., 2001] for a surface could indicate
 79 that topography is the result of a single geologic process that operates at
 80 many scales. A break in the slope of RMS deviation at a given baseline (i.e.,
 81 a change in Hurst exponent) may imply that more than one process is play-
 82 ing a role in influencing the observed topography, usually with one process
 83 influencing shorter baselines and another affecting longer baselines. Finally,
 84 RMS deviation is a straight-forward measurement easing interpretation of
 85 surface roughness maps.

86 This study presents the first global maps of surface roughness of an aster-
 87 oid with baselines ranging from 4–200 m. We break the study into five parts,
 88 beginning with a discussion of the methodology employed to calculate and
 89 grid surface roughness measurements across Eros. This is not as straightfor-
 90 ward as previous global surface roughness assessments on planets given the
 91 irregular and elongate shape of Eros. We present our resulting global sur-
 92 face roughness maps projected onto a shape model of 433 Eros and discuss
 93 the extent to which the surface roughness is correlated with various geologic
 94 features. We complete our efforts by discussing the geology of Eros in terms

95 of the measured surface roughness, which, as on Itokawa, can provide an
96 estimate of the mobile portion of the regolith on Eros.

97 In this study, we use common names in the literature for the largest crater
98 on Eros (see Fig. 1). The crater Shoemaker (12°S 25°E, called Charlois Re-
99 gio by the International Astronomical Union, IAU), is the youngest crater
100 of the three discussed here and is 7.6 km in diameter (Thomas et al., 2001).
101 Shoemaker overlaps the crater Himeros (5°N 75°E), which is 10 km in di-
102 ameter. Psyche (15°N 275°E) is on the opposite side of Eros and is 5.3 km
103 in diameter. The naming convention for Charlois Regio/Shoemaker in this
104 paper is used for consistency with previous studies (e.g., Cheng et al., 2002;
105 Buczkowski et al., 2008) and for the rest of the paper we will refer to Charlois
106 Regio as Shoemaker crater.

107 2. Methodology

108 We used topography data (Fig. 1) for Eros from the NLR instrument that
109 flew aboard the NEAR-Shoemaker spacecraft (Zuber et al., 1997). NLR col-
110 lected over 16 million returns while in orbit around Eros from February 2000
111 to February 2001 (Cheng et al., 2002). Individual NLR transects or tracks are
112 composed of a series of altimetric returns collected as the spacecraft traveled
113 forward. We use these individual NLR tracks instead of derived topography
114 in the form of digital terrain maps (DTMs) that are available for NLR data.
115 DTMs are often generated by binning and interpolating the altimetric data
116 (see discussion in Glaze et al., 2003; Barnouin-Jha et al., 2005). Making use
117 of individual altimetry tracks is particularly important for NLR data col-
118 lected at Eros because radial spacecraft trajectory uncertainties could result

119 in differences of up to 100 m between individual NLR tracks, although on
 120 average they differ by a RMS value of 22 m (Miller et al., 2002; Kahn et al.,
 121 2015). Additionally, the precision of individual NLR returns is 0.312 m
 122 (Cheng et al., 2002) and we use this value as our precision for surface rough-
 123 ness measurements. During binning for DTM production, these uncertainties
 124 can influence the inferred surface shape. In such situations, it is desirable
 125 to measure roughness along individual NLR tracks, where the topography
 126 measured is self-consistent. The penalty for using NLR data, rather than
 127 DTMs derived from NLR or imaging is that the density of NLR data across
 128 Eros is non-uniform leading to some loss of spatial coverage. However, this
 129 lack of spatial coverage is traded against higher accuracy surface roughness
 130 measurements derived from the higher precision NLR data.

131 We measured surface roughness using RMS deviation as has been done
 132 in previous studies of the meter-scale surface roughness of asteroids (Cheng
 133 et al., 2001, 2002; Abe et al., 2006; Barnouin-Jha et al., 2008). We calculated
 134 RMS deviation using methodology from Susorney et al. (2017), but modified
 135 to take into account the complex, non-ellipsoid, 3-dimensional geometry of
 136 Eros. Topography was detrended at ten-times the horizontal scale (baseline)
 137 used for estimating surface roughness before surface roughness calculations
 138 were made. This detrending removed broad-scale topography following the
 139 recommendations of Shepard et al. (2001). In what follows, we discuss the
 140 nature of the NLR data and define RMS deviation. Furthermore, we present
 141 how we processed and filtered the NLR data when computing RMS deviation,
 142 and show how the results are gridded and mapped across the asteroid. We
 143 also explain the derivation of the Hurst exponents for Eros.

144 2.1. NLR data

145 The NLR instrument operated continuously while the NEAR spacecraft
146 was in orbit. The distances between individual NLR footprints (Fig. 2) was
147 primarily a function of the orbital speed and distance to the surface of Eros
148 (Zuber et al., 2000). Fig. 2a shows that the majority of NLR points are less
149 than 4 m apart and we used this value as our smallest baseline for surface
150 roughness measurements. We used a maximum baseline of 200 m because
151 we needed to detrend the track over a spatial scale 10 times the baseline
152 of interest and the tracks used were only several kilometers long for reasons
153 presented below.

154 A combination of NEAR-Shoemaker orbits, the shape of Eros, and changes
155 in spacecraft pointing was such that many NLR tracks are not straight lines
156 across the surface of Eros. The methodology we employ for measuring the
157 distance between returns and detrending the NLR data requires the tracks to
158 be as straight as possible for best results in estimating the distance between
159 NLR returns. We filtered the NLR tracks to ‘cut’ them at points when the
160 tracks changed in direction using an automated methodology. We looked
161 for abrupt changes in NLR track longitude. This method was conservative
162 and resulted in shorter NLR tracks, but a more reliable horizontal distance
163 estimates between NLR points and detrend the data appropriately.

164 2.2. RMS deviation

165 RMS deviation $[\nu(L)]$ is the root-mean-square (RMS) of the change in
166 topography over a baseline (Shepard et al., 2001). It is defined as the follow-
167 ing,

$$\nu(L) = \left\{ \frac{1}{n} \sum_{i=1}^n [\Delta h(L)_i]^2 \right\}^{\frac{1}{2}}, \quad (1)$$

where $\Delta h(L)$ is the change in height over a given baseline, L , and n is the number of Δh used in the calculation of RMS deviation. $\nu(L)$ is known to fluctuate below a threshold value of n for planetary surfaces (Kreslavsky et al., 2013; Shepard et al., 2001; Rosenberg et al., 2011; Susorney et al., 2017), Fig. 2b shows the stability of the estimate of $\nu(L)$ for a single location on Eros. From analyzing many locations on Eros, we found RMS deviation becomes stable when $n \sim 200$; similar to results for Mercury (Susorney et al., 2017). Therefore, we use a minimum of 200 Δh when calculating $\nu(L)$.

2.3. NLR track filtering and surface roughness calculation

Calculating $\nu(L)$ from NLR tracks cannot be done in the same manner as for planets due to the irregular shape of 433 Eros. We expanded upon a methodology for uneven track spacing developed in Susorney et al. (2017), but adapt it for the 3-dimensional geometry of an asteroid. We start by using individual ‘cut’ NLR tracks and then calculate the geopotential elevation (i.e., topography) from a geoid generated from an NLR track-derived shape model, assuming a homogeneous distribution of mass with a density of 2.67 g/cm^3 and a rotation rate of 0.000331 radians/second (Abe et al., 2006). We use topography rather than surface shape since, for irregular bodies, the surface shape and topography can differ dramatically.

We evaluated each NLR point on each track to calculate Δh . Then we calculated the ‘true’ distance between NLR points on the ‘cut’ tracks within 500 m (measured as a straight-line distance) of the NLR point being inves-

190 tigated using a modification of the methods outlined in Cheng et al. (2001,
 191 2002) and Barnouin-Jha et al. (2008). The distance was calculated by fitting
 192 the x, y, and z coordinates of the NLR track as a straight-line function of
 193 time, to capture some of the curvature of Eros. We measured the distance
 194 between returns along this line. Once we calculated distance, we found all
 195 the points within $5L$ on either side of the point. We then linearly interpo-
 196 lated the NLR points to produce topography with the spacing of L and then
 197 detrended the interpolated track $10 L$. In Susorney et al. (2017) interpo-
 198 lated tracks were compared to tracks without interpolation and no statistical
 199 difference in surface roughness was found between both methodologies. Fi-
 200 nally, the Δh from the two adjacent topography points was measured. This
 201 methodology was repeated for all NLR points at all baselines.

202 *2.4. Shape model gridding*

203 The gridding and projecting of surface roughness maps were done on a
 204 3-dimensional shape model of Eros. We used the 3-dimensional shape model
 205 to avoid the distortion of projecting an irregular object unto a map designed
 206 for a sphere. For our maps, we degraded a shape model of Eros (Gaskell,
 207 2008) into a 2000 plate model so that we had sufficient Δh for each plate. On
 208 average, the surface area of each plate is 0.562 km^2 , making each plate about
 209 0.05 % of the total surface area of the asteroid. For each L , all Δh values
 210 within $2L$ and $\nu(L)$ were calculated using Equation 1. If less than 200 Δh
 211 values were present, we did not calculate $\nu(L)$ and the plate is represented
 212 as a gray plate in our maps.

213 2.5. Hurst exponent

214 RMS deviation is related to the self-affine nature of many planetary sur-
215 faces through a value called the Hurst exponent, H . The Hurst exponent can
216 be measured if the surface roughness when plotted as the log of RMS devi-
217 ation versus the log of baseline (the plot is called a devigram) is a straight
218 line (Turcotte, 1997; Shepard et al., 2001). The Hurst exponent is defined as
219 the following,

$$\nu(L) = \nu_o L^H, \quad (2)$$

220 where ν_o is the RMS deviation at the unit scale, m, (Shepard et al., 2001).
221 We estimate H for each plate, for the entire asteroid, and for Shoemaker
222 crater.

223 3. Results

224 In this section, we present 3-dimensional shape models with the RMS
225 deviation calculated for each plate. We discuss ‘small-scale’ , $L = 4\text{--}10$ m,
226 ‘medium-scale’ , $L = 20\text{--}90$ m, and ‘large-scale’ , $L = 100\text{--}200$ m baselines
227 separately. We present a representative map for each category. A map of the
228 Hurst exponents for each plate and a global devigram is also shown. The
229 different baseline categories and representative maps were chosen to high-
230 light different spatial variations in surface roughness found in each baseline
231 category.

232 3.1. Small-scale roughness 4-10 m

233 At $L = 5\text{m}$ (Fig. 3), there are high surface roughness values in the three
234 largest craters on the surface (Psyche, Himeros, and Shoemaker). The largest

235 spatial region of elevated roughness values is in Shoemaker, the youngest
236 crater of the three (Thomas et al., 2001).

237 *3.2. Medium-scale roughness 20-100 m*

238 At the $L = 50$ m baseline (Fig. 4), the three largest craters have slightly
239 elevated surface roughness values, but to a lesser degree than in the small-
240 scale maps.

241 *3.3. Large-scale roughness 100-250 m*

242 At the largest baselines (Fig. 5) the surface roughness values are lowest in
243 the large craters Himeros and Shoemaker. A band of lower surface roughness
244 values wraps around the southern edge of Himeros and Shoemaker continuing
245 around the nose to the north. The crater Psyche’s surface roughness values
246 are indistinguishable from surrounding surface roughness values.

247 *3.4. Deviogram and Hurst exponents*

248 Deviograms for the entire surface of 433 Eros and the crater Shoemaker
249 are shown in Fig 6. The surface of Eros is self-affine with an overall Hurst
250 exponent of 0.97 ± 0.01 . The ν_o of Eros is 0.14 ± 0.01 m. The deviogram for
251 the crater Shoemaker shows the observed trend of Shoemaker having higher
252 surface roughness values than the rest of Eros at small baselines and lower
253 surface roughness values than the rest of Eros at large baselines as seen in
254 Figs 3-5.

255 A map of the Hurst exponent calculated for each plate is shown in Fig 7.
256 The Hurst exponent is lowest in the craters Shoemaker and Himeros and is
257 close to ~ 1 in the crater Psyche.

258 4. Geologic Processes and Surface Roughness

259 In this section, we focus on relating the observed surface roughness on
260 Eros to various geologic processes. The boulder and crater counts used in
261 the following section were kindly provided by P.C. Thomas (Thomas et al.,
262 2002; Thomas and Robinson, 2005).

263 4.1. Boulders

264 The highest density of boulders (> 16 m in diameter, Fig. 9) is found
265 in Shoemaker crater. A positive weak ($r = 0.21$) but statistically significant
266 correlation ($p = 1.4e-05$) can be found across the entire surface of the aster-
267 oid between the surface roughness computed at $L = 5$ m and boulder density
268 when a given plate of the low resolution 2000-plate Eros shape model has
269 more than 15 boulders present. We calculated a Pearson correlation coeffi-
270 cient for all of our correlation tests with an N of 2000 (for the 2000 plate
271 model) and assumed the results were statistically significant if p was less than
272 0.05. Given that for many regions of Eros there is a deficit of craters under
273 100 m in diameter (Chapman et al., 2002) especially in Shoemaker crater
274 (Thomas and Robinson, 2005), and evidence for the presence of boulders in
275 images, the correlation result is consistent with boulders providing the main
276 contributions to surface roughness measured at small baselines on Eros.

277 4.2. Cratering

278 The lowest density of impact craters (177 - 1000 m in diameter, Fig. 8)
279 is found in Shoemaker and Himeros craters, which corresponds to the lowest
280 surface roughness values at long baselines. The band of low surface roughness
281 values around the craters Himeros and Shoemaker (a region of low surface

roughness values at $L = 100\text{--}200$ m, Fig. 5) corresponds to a region of low crater density (Fig. 8). We found a positive weak correlation ($r = 0.44$) between surface roughness at 100 m and impact crater density and a positive moderate correlation ($r = 0.54$) at 200 m, both correlations were statistically significant ($p = 1.8\text{e-}22$ and $9.6\text{e-}30$ respectively).

4.3. *Tectonics*

The surface of Eros is covered in structural lineaments (Buczkowski et al., 2008). Past studies of the surface roughness of Eros noted that the surface roughness values from individual NLR tracks increased at structural lineaments (Cheng et al., 2002). We checked for a correlation between the density of lineaments that intersected a plate and surface roughness at baselines of 4 - 200 m and no statistical correlation was found. We also checked for any visual correlation between the maps and did not observe any correlation.

4.4. *Ponds*

Ponds are nearly flat deposits on asteroids such as Eros whose origin is debated (Roberts et al., 2014). In images, ponds appear smooth down to 1.2 cm per pixel resolution (Robinson et al., 2001). While these ponds have been described as qualitatively smooth (e.g., Robinson et al., 2001) no quantitative study of their surface roughness has been performed. Ponds range in size from 7–210 m, the scale of our roughness measurements (Robinson et al., 2001; Thomas et al., 2002; Roberts et al., 2014). We checked for a correlation with our global surface roughness measurements with a map of pond density generated from Roberts et al. (2014) at $L = 5, 10$, and 20 m. We found no correlation with surface roughness and pond density. This is not surprising

306 given the relatively small size and number of ponds. They do not significantly
307 influence the global surface roughness of Eros at baselines we measured.

308 *4.5. Slope and Geopotential Elevation*

309 We investigated the possibility of correlations between slope and geopo-
310 tential elevation and surface roughness. In Cheng et al. (2002) a visual cor-
311 relation was found between regions of high slope and regions of high surface
312 roughness. We calculated the slope and geopotential elevation for a 49,152
313 plate shape model of Eros and used his data to calculate the average slope
314 and geopotential elevation for our degraded 2000 plate model. We looked
315 for a correlation with slope and geopotential elevation for all of the baselines
316 measured here and found none.

317 **5. Discussion**

318 *5.1. Geologic processes on Eros and surface roughness*

319 The surface roughness of Eros is dominated by two main geologic features:
320 impact craters and boulders. Impact crater density is correlated with sur-
321 face roughness above 100 m, consistent with previous observations for larger
322 planetary bodies including the Moon (Rosenburg et al., 2011) and Mercury
323 (Kreslavsky et al., 2014; Fa et al., 2016; Susorney et al., 2017). Boulder den-
324 sity is statistically correlated with the global surface roughness of Eros at the
325 baseline of 5 m.

326 The distribution of large boulders and small to intermediate sized craters
327 on Eros is linked to the most recent large impact on the surface (the forma-
328 tion of Shoemaker and subsequent seismic shaking from the impact) (Thomas

329 and Robinson, 2005). A deficit of impact craters near the impact site (seen
330 in the low surface roughness density at long baselines) and a deficit of craters
331 in straight-line distance from the crater center (representing travel time for
332 seismic waves) are proposed to be due to seismic shaking (Thomas and Robin-
333 son, 2005). The boulder density also follows the expected ejecta distribution
334 from the Shoemaker impact (Thomas et al., 2001), which is correlated to the
335 surface roughness at $L = 5$ m. While the boulder and crater distributions
336 are different they are linked by the formation of the crater Shoemaker.

337 Previous studies of localized surface roughness on Eros have identified lin-
338 eaments as sources of high surface roughness values (Cheng et al., 2002). We
339 did not see evidence of correlations between maps of the density of tectonic
340 lineaments and maps of surface roughness. The lack of correlation may be
341 due to two factors: the need for large plates (required to keep RMS deviation
342 from fluctuating) in mapping surface roughness and the relatively localized
343 nature of lineaments. Further, lineaments do not generate substantial topog-
344 raphy, meaning they are unlikely to be the source of surface roughness to the
345 same extent as boulders and craters.

346 The rim of Psyche was found to have higher surface roughness values than
347 the crater walls in a previous study of the surface roughness of Eros (Cheng
348 et al., 2002) at all L measured (5–1000 m). This observation may be due to
349 not detrending the topography before calculating surface roughness and thus
350 previous measures of surface roughness of Eros may have been measuring
351 the slope rather than the surface roughness. However, some regions (plates)
352 within Psyche possess higher surface roughness relative to the rim in our
353 study ($L = 50$ m). Cheng et al. (2002) proposed that such higher surface

roughness values on the crater wall were indicative of exposure of bedrock. Cheng et al. (2002) also noted higher surface roughness values near high slopes and this was also interpreted as evidence of exposure of bedrock. It was postulated that on high slopes regolith could have slid off the slopes, and exposed bedrock with higher surface roughness values. We could not find a significant correlation between surface roughness and slope. If there is an increase in surface roughness values on slopes it is not a global enough phenomena that a global map would detect it. It could also simply mean that bedrock (if exposed) is similar in surface roughness to regolith or that no bedrock is exposed. We can compare the measurements of Eros' surface roughness to past studies of surface roughness from Eros and other bodies (Table. 1) and find that our values for the surface roughness of Eros are higher than previous studies. This could be due to including the global dataset in our calculations (including smoother regions that were not studied previously) and updated methodologies.

5.2. *Regolith*

For small baselines on Eros (under 10 m) boulders are the likely source of variations in surface roughness consistent with previous studies of Eros and Itokawa (Cheng et al., 2001, 2002; Abe et al., 2006; Barnouin-Jha et al., 2008). This observation was used on Itokawa to estimate a lower bound on regolith thickness (Barnouin-Jha et al., 2008) due to the evidence that regolith appears to cover boulders and embays the lowland (Miyamoto et al., 2007; Barnouin-Jha et al., 2008). Other evidence for regolith mobility on Itokawa includes the imbrication of adjacent boulders in the direction of slope (Miyamoto et al., 2007).

379 Eros has a layer of tens of meters of regolith that has covered boulders
 380 to varying degrees (Fig. 11) and is mobile as seen by the flat floors at
 381 the bottom of some craters (Veverka et al., 2001; Robinson et al., 2002;
 382 Dombard et al., 2010) and imbrication of boulders (Barnouin et al., 2012). If
 383 small-scale surface roughness ($L = 5$ m) is due primarily to regolith covering
 384 boulders and infilling other changes in topography (Fig 10) we can derive
 385 a lower limit on regolith thickness from the difference in surface roughness
 386 measurements at small baselines for different regions of Eros. This assumes
 387 that at times in the past boulders covered all of Eros, but we believe this
 388 is likely because of the Eros has several large craters that must have left
 389 behind large populations of boulders strewn across the asteroid. This was
 390 observed on Lutetia by Thomas et al. (2012), for example, where each crater
 391 left behind boulders around all the large observed craters. We estimated the
 392 thickness of mobile regolith that could cover older boulders by comparing the
 393 1st and 3rd quartile of RMS deviation from the 2000 plate model at $L = 5$ m
 394 and found the difference in surface roughness to be 0.2 m. The difference in
 395 maximum surface roughness value and minimum surface roughness at $L = 5$
 396 m is 6.2 m. This produces a range in mobile regolith for Eros of 0.2–6.2 m,
 397 less than estimates for total regolith thickness of Eros (Veverka et al., 2001;
 398 Robinson et al., 2002) derived from infilled craters, but similar to estimates
 399 for Itokawa (2.3 ± 0.4) (Barnouin-Jha et al., 2008).

400 This estimate of the thickness of the mobile regolith possess does not take
 401 into account other processes that could alter the assumptions made. For ex-
 402 ample processes such as shaking-induced assortment, the "Brazil nut effect"
 403 which causes larger particles to reach the surface (e.g., Murdoch et al., 2015).

404 We believe this effect is probably not very important on Eros, where many
 405 blocks (other than the ones directly linked to Shoemaker crater formation)
 406 tend to be located at local slope minima, near the bottom of craters. Maybe
 407 of bigger concern than the brazil nut effect, is the assumption that boulders
 408 evenly covered the surface after the formation of the many large craters on
 409 Eros, and that they were not intimately mixed with finer regolith as might
 410 be expected for ejecta deposits. The evidence presented previously for Lute-
 411 tia, as well as observation of small lunar craters (Krishna and Kumar, 2016),
 412 indicates that it is very likely blocks are often the last ejecta components
 413 that fall on top of the finer ejecta. So while some caveats exist, our rough-
 414 ness assessment suggest some evidence for a mobile regolith layer that is on
 415 the order of 0.2 to 6.2 m that reduces surface roughness values by covering
 416 existing blocks with finer materials.

417 *5.3. Comparisons of Eros to other planetary bodies*

418 Deviograms provide a quantitative way to compare the surface roughness
 419 on different bodies where similar baselines of surface roughness have been
 420 measured. In Fig. 6, we compare Eros to a devigram of the Moon [calculated
 421 for this study, using the same methodology in Susorney et al. (2017)] for a
 422 region of the lunar mare and lunar highlands. Both the lunar highlands
 423 and mare are smoother than Eros possibly due to the retention of more
 424 ejecta on the moon, which infills topography producing a smoother surface.
 425 Two devigrams of the surface roughness of Itokawa (Barnouin-Jha et al.,
 426 2008) are also shown in Fig. 6. The lowlands of Itokawa (Muses-C) have
 427 lower surface roughness values than the global Eros devigram at the same
 428 baselines and the highlands of Itokawa match the global surface roughness

429 values of Eros. A caveat to comparing Barnouin-Jha et al. (2008) to our
 430 study is that Barnouin-Jha et al. (2008) did not detrend topography before
 431 calculating surface roughness, although they used flat regions. The similarity
 432 of values of Eros and the highlands of Itokawa is likely due to the presence
 433 of blocks on both Eros and the highlands of Itokawa.

434 Eros and the Moon have similarly shaped devioigrams and are both self-
 435 affine. Itokawa is not self-affine and the devioigram is flat (Barnouin-Jha
 436 et al., 2008). The similarity in devioigram shape between the Moon and
 437 Eros and the difference in devioigram shape between Eros and Itokawa imply
 438 that the subsurface of Eros has strength and can support topography (unlike
 439 Itokawa, a rubble-pile). This implies that the shape of the devioigram may
 440 be diagnostic of the interior structure of asteroids. Future measurements of
 441 the meter-scale surface roughness of asteroids will allow us to explore this
 442 relationship between devioigram shape and sub-surface structure.

443 The Hurst exponent of the lunar highlands and the mare are 0.95 and 0.76
 444 respectively for baselines of 17–2700 m (Rosenburg et al., 2011). The Hurst
 445 exponent for Mercury’s cratered terrain is 0.95 ± 0.01 for baselines of 500–
 446 1500 m (Susorney et al., 2017). Both the lunar highlands (the more heavily
 447 cratered region of the moon) and the mercurian cratered terrain (the more
 448 heavily cratered terrain of Mercury) have similar Hurst exponents to Eros
 449 (0.97 ± 0.01). This suggests that Hurst exponents ~ 1 might be indicative
 450 of surfaces dominated by impact cratering. The Hurst exponent for the
 451 interior of Shoemaker (a region with fewer impact craters) is 0.64 ± 0.2 giving
 452 additional evidence to support the theory that higher Hurst exponents are
 453 indicative of surfaces dominated by cratering. Finally, Itokawa, an asteroid

454 with very few obvious craters, (Saito et al., 2006) is not self-affine and a
455 Hurst exponent could not be fit (Barnouin-Jha et al., 2008).

456 A question does arise to the theory that higher Hurst exponents are in-
457 dicative of a crater dominated surface when looking at Eros. How can the
458 Hurst exponent be indicative of cratering if the Hurst exponent includes sur-
459 face roughness values from baselines that are not sensitive to impact cratering
460 (i.e., baselines dominated by boulders)? One explanation of the Hurst expo-
461 nent continuing to smaller baselines is that block distribution on Eros is a
462 result of cratering and the surface roughness is still fundamentally a function
463 of impact cratering. If the surface is missing one part of this scenario (either
464 blocks or craters) the Hurst exponent decreases, like in Shoemaker ($H =$
465 0.63 ± 0.02) where very few craters are present. The Hurst exponent may
466 be indicative of both the crater cavity (at larger baselines) and blocks from
467 the crater’s ejecta (at smaller baselines). Another explanation is that the
468 Hurst exponent is not indicative of a single geologic process at all and there
469 is some other reason that the Hurst exponent is similar in multiple terrains
470 that are dominated by cratering. The results of this study cannot provide
471 a definitive answer, but by continuing to measure the surface roughness of
472 different bodies in the solar system we can gather more data to understand
473 what the Hurst exponent says about the origin and evolution of the surfaces
474 of planetary bodies.

475 5.4. *Comparison of surface roughness of Eros from NLR to surface roughness* 476 *derived from thermophysical models*

477 As mentioned previously, RMS deviation (or the related measure of RMS
478 slope) is used by the thermal inertia community to quantify the surface rough-

479 ness of asteroids. A previous study has investigated the surface roughness
 480 of Eros using thermal-infrared observations and a thermophysical model to
 481 calculate RMS slope at a baseline of 0.005 m (Rozitis, 2017). Using the Hurst
 482 exponent (and assuming the Hurst exponent stays constant down to the rel-
 483 evant baseline of 0.005 m) we can calculate RMS deviation at 0.005 m to
 484 compare the results of this paper to Rozitis (2017). A large caveat to such a
 485 comparison is the strong likelihood that the Hurst exponent would vary from
 486 baselines of meters to baselines of centimeters. A previous study extrapo-
 487 lated on Mars found that the Hurst exponent differs from baselines of meters
 488 to baselines of kilometers due to the different geologic processes controlling
 489 surface roughness at such scales (Campbell, 2003). With this caveat in mind,
 490 we calculated the surface roughness at a scale of 0.005 m (the scale measured
 491 in Rozitis (2017)) using our measurement of the global Hurst exponent and ν_o
 492 and found a measure of the surface roughness of 0.082 ± 0.001 m. This com-
 493 pares to the surface roughness measured by Rozitis (2017) of 0.0039 ± 0.001
 494 m. They reported their measurement in RMS slope ($38 \pm 8^\circ$), but RMS slope
 495 can be converted into RMS deviation by multiplying tangent of RMS slope
 496 by the baseline Shepard et al. (2001). The RMS deviation calculated using
 497 our Hurst exponent and the measurement calculated by thermal-infrared ob-
 498 servations and thermophysical modeling differs outside each of the respected
 499 error bars. The source of this discrepancy is likely the change in Hurst ex-
 500 ponent at smaller scales. The Hurst exponent at the baselines measured in
 501 our paper is controlled by the interplay of boulders and impact craters pro-
 502 ducing topography on Eros. At a baseline of centimeters to sub-centimeters
 503 different surface processes are controlling topography including regolith size

504 and even the texture of individual regolith grains. Additionally, the age of
505 the surface could control surface roughness at smaller scales since thermal
506 effects and micrometeorites could change the surface roughness at the scale
507 of centimeters. The surface roughness at smaller scales could be driven by
508 different processes which would make a straight downward continuation of the
509 Hurst exponent unlikely for the global surface.

510 We can investigate the relationship between NLR-derived surface rough-
511 ness and the thermophysical modeling-derived surface roughness further in
512 two ways. In the first investigation, we can hold the surface roughness mea-
513 surement from Rozitis (2017) constant and assume the Hurst exponent is
514 constant to small baselines, but allow the baseline of the Rozitis (2017) to
515 change. Using Eqn. (2) we find that a baseline of 0.025 m (2.5 cm) matches
516 both of these criteria. Second, we can assume the Hurst exponent changes
517 at the 1 m baseline, and keep the surface roughness measurement and base-
518 line from Rozitis (2017) constant and find the Hurst exponent that would
519 fit the data. This results in a Hurst exponent of 0.67. Both of these small
520 investigations raise new possibilities. The change of the baseline in the first
521 investigation results in a baseline of surface roughness measurements that
522 could be possible for thermophysical modeling-derived surface roughness, as
523 the baseline the surface roughness is measured over is not as clear as in laser
524 altimeter-derived surface roughness Rozitis and Green (2012). In the second
525 investigation, the changing of the Hurst exponent resulted in a Hurst expo-
526 nent that has been observed on planetary surfaces (Shepard et al., 2001).
527 The discrepancy between the two datasets will likely only be resolved when
528 high-resolution topographic measurements of asteroids are performed allow-

ing laser altimeter-derived surface roughness to be calculated at centimeter
and smaller scale baselines.

6. Conclusion

In this study, we undertook the first global mapping of the meter-scale surface roughness of 433 Eros. The global surface roughness of Eros is self-affine with a Hurst exponent of 0.97 ± 0.01 . Boulders and impact craters produce the surface roughness at different scale lengths on Eros, the crater Shoemaker, in particular, has higher surface roughness values relative to the rest of Eros at small baselines (due to the high density of boulders) and low surface roughness values compared to the rest of Eros at large baselines (due to the low density of impact craters). It is likely that a single event, the formation of Shoemaker, shaped the surface roughness of Eros at all baselines measured. Surface roughness is not correlated with tectonic lineaments, ponds, or slope on a global level. The thickness of mobile regolith that infills topography and covers boulders is estimated to be 0.2–6.2 m. By comparing Eros to surface roughness measurements from other bodies in the solar system we suggest that a Hurst exponent of near ~ 1 may be indicative of a surface dominated by impact cratering. The surface roughness (deviogram and Hurst exponent) of Eros is more lunar-like than Itokawa-like suggesting the interior has strength to support larger-scale topography.

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559 **References**

- 560 Abe, S., Mukai, T., Hirata, N., Barnouin-Jha, O. S., Cheng, A. F., Demura,
561 H., Gaskell, R. W., Hashimoto, T., Hiraoka, K., Honda, T., Kubota, T.,
562 Matsuoka, M., Mizuno, T., Nakamura, R., Scheeres, D. J., Yoshikawa,
563 M., Jun. 2006. Mass and local topography measurements of Itokawa by
564 Hayabusa. *Science* 312 (5778), 1344–1347.
- 565 Barnouin, O. S., Gaskell, R. W., Ernst, C. M., May 2012. Revisiting the
566 NEAR-Shoemaker landing site. *Asteroids, Comets, Meteors* 2012 1667.
- 567 Barnouin-Jha, O. S., Baloga, S., Glaze, L., Apr. 2005. Comparing landslides
568 to fluidized crater ejecta on Mars. *Journal of Geophysical Research* 110 (E),
569 4010.
- 570 Barnouin-Jha, O. S., Cheng, A. F., Mukai, T., Abe, S., Hirata, N., Naka-
571 mura, R., Gaskell, R. W., Saito, J., Clark, B. E., Nov. 2008. Small-scale
572 topography of 25143 Itokawa from the Hayabusa laser altimeter. *Icarus*
573 198 (1), 108–124.

574 Benner, L. A. M., Ostro, S. J., Magri, C., Nolan, M. C., Howell, E. S.,
 575 Giorgini, J. D., Jurgens, R. F., Margot, J.-L., Taylor, P. A., Busch, M. W.,
 576 Shepard, M. K., Dec. 2008. Near-Earth asteroid surface roughness depends
 577 on compositional class. *Icarus* 198 (2), 294–304.

578 Buczkowski, D. L., Barnouin-Jha, O. S., Prockter, L. M., Jan. 2008. 433 Eros
 579 lineaments: Global mapping and analysis. *Icarus* 193 (1), 39–52.

580 Campbell, B. A., 2003. Limits on inference of Mars small-scale topography
 581 from MOLA data. *Geophysical Research Letters* 30 (3), 1116.

582 Chapman, C. R., Merline, W. J., Thomas, P. C., Joseph, J., Cheng, A. F.,
 583 Izenberg, N., Jan. 2002. Impact History of Eros: Craters and Boulders.
 584 *Icarus* 155 (1), 104–118.

585 Cheng, A. F., Barnouin-Jha, O., Prockter, L., Zuber, M. T., Neumann, G.,
 586 Smith, D. E., Garvin, J., Robinson, M., Veverka, J., Thomas, P., Jan. 2002.
 587 Small-Scale Topography of 433 Eros from Laser Altimetry and Imaging.
 588 *Icarus* 155 (1), 51–74.

589 Cheng, A. F., Barnouin-Jha, O., Zuber, M. T., Veverka, J., Smith, D. E.,
 590 Neumann, G. A., Robinson, M., Thomas, P., Garvin, J. B., Murchie, S.,
 591 Chapman, C., Prockter, L., Apr. 2001. Laser altimetry of small-scale fea-
 592 tures on 433 Eros from NEAR-Shoemaker. *Science* 292 (5516), 488–491.

593 Dombard, A. J., Barnouin, O. S., Prockter, L. M., Thomas, P. C., Dec. 2010.
 594 Boulders and ponds on the Asteroid 433 Eros. *Icarus* 210 (2), 713–721.

595 Fa, W., Cai, Y., Xiao, Z., Tian, W., Apr. 2016. Topographic roughness of the

596 northern high latitudes of Mercury from MESSENGER Laser Altimeter
597 data. *Geophysical Research Letters*, doi:10.1002–2016GL068120.

598 Fujiwara, A., Kawaguchi, J., Yeomans, D. K., Abe, M., Mukai, T., Okada,
599 T., Saito, J., Yano, H., Yoshikawa, M., Scheeres, D. J., Barnouin-Jha,
600 O., Cheng, A. F., Demura, H., Gaskell, R. W., Hirata, N., Ikeda, H.,
601 Kominato, T., Miyamoto, H., NAKAMURA, A. M., Nakamura, R., Sasaki,
602 S., Uesugi, K., Jun. 2006. The Rubble-Pile Asteroid Itokawa as Observed
603 by Hayabusa. *Science* 312 (5), 1330–1334.

604 Garvin, J. B., Frawley, J. J., Abshire, J. B., 1999. Vertical roughness of
605 Mars from the Mars Orbiter Laser Altimeter. *Geophysical Research Letters*
606 26 (3), 381–384.

607 Gaskell, B., 2008. Gaskell Eros Shape Model V1.0. NEAR-A-MSI-5-
608 EROSSHAPE-V1.0. NASA Planetary Data System.

609 Glaze, L. S., Baloga, S. M., Stofan, E. R., Sep. 2003. A methodology for
610 constraining lava flow rheologies with MOLA. *Icarus* 165 (1), 26–33.

611 Harris, A. W., Lagerros, J. S. V., 2002. Asteroids in the Thermal Infrared.
612 In: Bottke, W. F. (Ed.), *Asteroids III*. Tucson.

613 Kahn, E. G., Barnouin, O. S., Daly, M. G., Johnson, C. L., Seabrook, J.,
614 Mar. 2015. Reconstruction of the Eros Shape Model Using NEAR Laser
615 Rangefinder Data. 46th Lunar and Planetary Science Conference 46, 2874.

616 Kreslavsky, M. A., Head, J. W., Nov. 2000. Kilometer-scale roughness of
617 Mars: Results from MOLA data analysis. *Journal of Geophysical Research:*
618 *Planets* (1991–2012) 105 (E11), 26695–26711.

619 Kreslavsky, M. A., Head, J. W., Neumann, G. A., 2014. Kilometer-scale
620 topographic roughness of Mercury: Correlation with geologic features and
621 units. *Geophysical Research Letters* 41, 1–7.

622 Kreslavsky, M. A., Head, J. W., Neumann, G. A., Rosenburg, M. A., Aharon-
623 son, O., Smith, D. E., Zuber, M. T., Oct. 2013. Lunar topographic rough-
624 ness maps from Lunar Orbiter Laser Altimeter (LOLA) data: Scale de-
625 pendence and correlation with geologic features and units. *Icarus* 226 (1),
626 52–66.

627 Krishna, N., Kumar, P. S., Jan. 2016. Impact spallation processes on the
628 Moon: A case study from the size and shape analysis of ejecta boulders
629 and secondary craters of Censorinus crater. *Icarus* 264 (C), 274–299.

630 Miller, J. K., Konopliv, A. S., Antreasian, P. G., Bordi, J. J., Chesley, S.,
631 Helfrich, C. E., Owen, W. M., Wang, T. C., Williams, B. G., Yeomans,
632 D. K., Jan. 2002. Determination of shape, gravity, and rotational state of
633 asteroid 433 Eros. *Icarus* 155 (1), 3–17.

634 Miyamoto, H., Yano, H., Scheeres, D. J., Abe, S., Barnouin-Jha, O., Cheng,
635 A. F., Demura, H., Gaskell, R. W., Hirata, N., Ishiguro, M., Michikami,
636 T., Nakamura, A. M., Nakamura, R., Saito, J., Sasaki, S., 2007. Regolith
637 migration and sorting on asteroid Itokawa. *Science* 316 (5827), 1011–1014.

638 Murdoch, N., Sánchez, P., Schwartz, S. R., Miyamoto, H., 2015. Asteroid
639 Surface Geophysics. *Asteroids IV*, 767–792.

640 Roberts, J. H., Kahn, E. G., Barnouin, O. S., Ernst, C. M., Prockter, L. M.,

641 Gaskell, R. W., Oct. 2014. Origin and flatness of ponds on asteroid 433
642 Eros. *Meteoritics & Planetary Science* 49 (10), 1735–1748.

643 Robinson, M. S., Thomas, P. C., Veverka, J., Murchie, S., Carcich, B., 2001.
644 The nature of ponded deposits on Eros. *Nature* 413 (6854), 396–400.

645 Robinson, M. S., Thomas, P. C., Veverka, J., Murchie, S. L., Wilcox, B. B.,
646 Dec. 2002. The geology of 433 Eros. *Meteoritics & Planetary Science*
647 37 (12), 1651–1684.

648 Rosenburg, M. A., Aharonson, O., Head, J. W., Kreslavsky, M. A., Mazarico,
649 E., Neumann, G. A., Smith, D. E., Torrence, M. H., Zuber, M. T., Feb.
650 2011. Global surface slopes and roughness of the Moon from the Lunar Or-
651 biter Laser Altimeter. *Journal of Geophysical Research* 116 (E2), E02001.

652 Rozitis, B., Jan. 2017. The surface roughness of (433) Eros as measured
653 by thermal-infrared beaming. *Monthly Notices of the Royal Astronomical*
654 *Society* 464 (1), 915–923.

655 Rozitis, B., Green, S. F., Jun. 2012. The influence of rough surface thermal-
656 infrared beaming on the Yarkovsky and YORP effects. *Monthly Notices of*
657 *the Royal Astronomical Society* 423 (1), 367–388.

658 Saito, J., Miyamoto, H., Nakamura, R., Ishiguro, M., Michikami, T., NAKA-
659 MURA, A. M., Demura, H., Sasaki, S., Hirata, N., Honda, C., Yamamoto,
660 A., Yokota, Y., Fuse, T., Yoshida, F., Tholen, D. J., Gaskell, R. W.,
661 Hashimoto, T., Kubota, T., Higuchi, Y., Nakamura, T., Smith, P., Hi-
662 raoka, K., Honda, T., Kobayashi, S., Furuya, M., Matsumoto, N., Nemoto,
663 E., Yukishita, A., Kitazato, K., Dermawan, B., Sogame, A., Terazono, J.,

664 Shinohara, C., Akiyama, H., Jun. 2006. Detailed Images of Asteroid 25143
665 Itokawa from Hayabusa. *Science* 312 (5), 1341–1344.

666 Shepard, M. K., Campbell, B. A., Bulmer, M. H., Farr, T. G., Gaddis, L. R.,
667 Plaut, J. J., Dec. 2001. The roughness of natural terrain: A planetary
668 and remote sensing perspective. *Journal of Geophysical Research* 106 (E),
669 32777–32796.

670 Susorney, H., Barnouin, O., Ernst, C., Byrne, P., 2017. Surface Roughness of
671 Mercury from MESSENGER. *Journal of Geophysical Research - Planets*.

672 Thomas, N., Barbieri, C., Keller, H. U., Lamy, P., Rickman, H., Rodrigo, R.,
673 Sierks, H., Wenzel, K. P., Cremonese, G., Jorda, L., Küppers, M., Marchi,
674 S., Marzari, F., Massironi, M., Preusker, F., Scholten, F., Stephan, K.,
675 Barucci, M. A., Besse, S., El-Maarry, M. R., Fornasier, S., Groussin, O.,
676 Hviid, S. F., Koschny, D., Kührt, E., Martellato, E., Moissl, R., Snodgrass,
677 C., Tubiana, C., Vincent, J. B., Jun. 2012. The geomorphology of (21)
678 Lutetia: Results from the OSIRIS imaging system onboard ESA’s Rosetta
679 spacecraft. *Planetary and Space Science* 66 (1), 96–124.

680 Thomas, P. C., Joseph, J., Carcich, B., Veverka, J., Clark, B. E., Bell, J. F.,
681 Byrd, A. W., Chomko, R., Robinson, M., Murchie, S., Prockter, L., Cheng,
682 A., Izenberg, N., Malin, M., Chapman, C., McFadden, L. A., KIRK, R.,
683 Gaffey, M., Lucey, P. G., Jan. 2002. Eros: Shape, topography, and slope
684 processes. *Icarus* 155 (1), 18–37.

685 Thomas, P. C., Robinson, M. S., Jul. 2005. Seismic resurfacing by a single
686 impact on the asteroid 433 Eros. *Nature* 436 (7049), 366–369.

687 Thomas, P. C., Veverka, J., Robinson, M. S., Murchie, S., 2001. Shoemaker
 688 crater as the source of most ejecta blocks on the asteroid 433 Eros. *Nature*
 689 413 (6854), 394–396.

690 Turcotte, D. L., Jul. 1997. *Fractals and Chaos in Geology and Geophysics*.
 691 Fractals and Chaos in Geology and Geophysics, Cornell University, New
 692 York.

693 Veverka, J., Robinson, M., Thomas, P., Murchie, S., Bell, J. F., Izenberg,
 694 N., Chapman, C., Harch, A., Bell, M., Carcich, B., Cheng, A., Clark, B.,
 695 Domingue, D., Dunham, D., Farquhar, R., Gaffey, M. J., Hawkins, E.,
 696 Joseph, J., KIRK, R., Li, H., Lucey, P., Malin, M., Martin, P., McFadden,
 697 L., Merline, W. J., Miller, J. K., Owen, W. M., Peterson, C., Prockter,
 698 L., Warren, J., Wellnitz, D., Williams, B. G., Yeomans, D. K., Sep. 2000.
 699 NEAR at Eros: Imaging and Spectral Results. *Science* 289 (5487), 2088–
 700 2097.

701 Veverka, J., Thomas, P. C., Robinson, M., Murchie, S., Chapman, C., Bell,
 702 M., Harch, A., Merline, W. J., Bell, J. F., Bussey, B., Carcich, B., Cheng,
 703 A., Clark, B., Domingue, D., Dunham, D., Farquhar, R., Gaffey, M. J.,
 704 Hawkins, E., Izenberg, N., Joseph, J., KIRK, R., Li, H., Lucey, P., Malin,
 705 M., McFadden, L., Miller, J. K., Owen, W. M., Peterson, C., Prockter, L.,
 706 Warren, J., Wellnitz, D., Williams, B. G., Yeomans, D. K., 2001. Imaging
 707 of small-scale features on 433 Eros from NEAR: Evidence for a complex
 708 regolith. *Science* 292 (5516), 484–488.

709 Wilkison, S. L., Robinson, M. S., Thomas, P. C., Veverka, J., McCoy, T. J.,
 710 Murchie, S. L., Prockter, L. M., Yeomans, D. K., Jan. 2002. An Estimate

711 of Eros's Porosity and Implications for Internal Structure. *Icarus* 155 (1),
 712 94–103.

713 Zuber, M., Smith, D., Cheng, A., Garvin, J., Aharonson, O., Cole, T., Dunn,
 714 P., Guo, Y., Lemoine, F., Neumann, G., Rowlands, D., Torrence, M., Sep.
 715 2000. The shape of 433 eros from the NEAR-shoemaker laser rangefinder.
 716 *Science* 289 (5487), 2097–2101.

717 Zuber, M. T., Smith, D. E., Cheng, A. F., Cole, T. D., Oct. 1997. The NEAR
 718 laser ranging investigation. *Journal of Geophysical Research* 102 (E),
 719 23761–23774.

Table 1: Surface roughness values from this study and other studies.

Object	L [m]	$\nu(10)$ [m]	H	
433 Eros	4–200	1.2	0.97 ± 0.01	This study
433 Eros	4–2000	~ 1	0.87	Cheng et al. (2001)
25143 Itokawa-Highlands	5–101	1.8	N/A	Barnouin-Jha et al. (2008)
25143 Itokawa-Lowlands	5–101	0.6	N/A	Barnouin-Jha et al. (2008)
Lunar-Mare	60–200	N/A	0.91 ± 0.01	This study
Lunar-Highlands	60–200	N/A	1.00 ± 0.02	This study
Lunar-Mare	17–2500	N/A	0.76	Rosenburg et al. (2011)
Lunar-Highlands	17–2500	N/A	0.95	Rosenburg et al. (2011)
Mercury-Cratered Terrain	500–250000	N/A	0.95 ± 0.01	Susorney et al. (2017)
Mercury-Smooth Plains	500–250000	N/A	0.88 ± 0.01	Susorney et al. (2017)

721 Figures

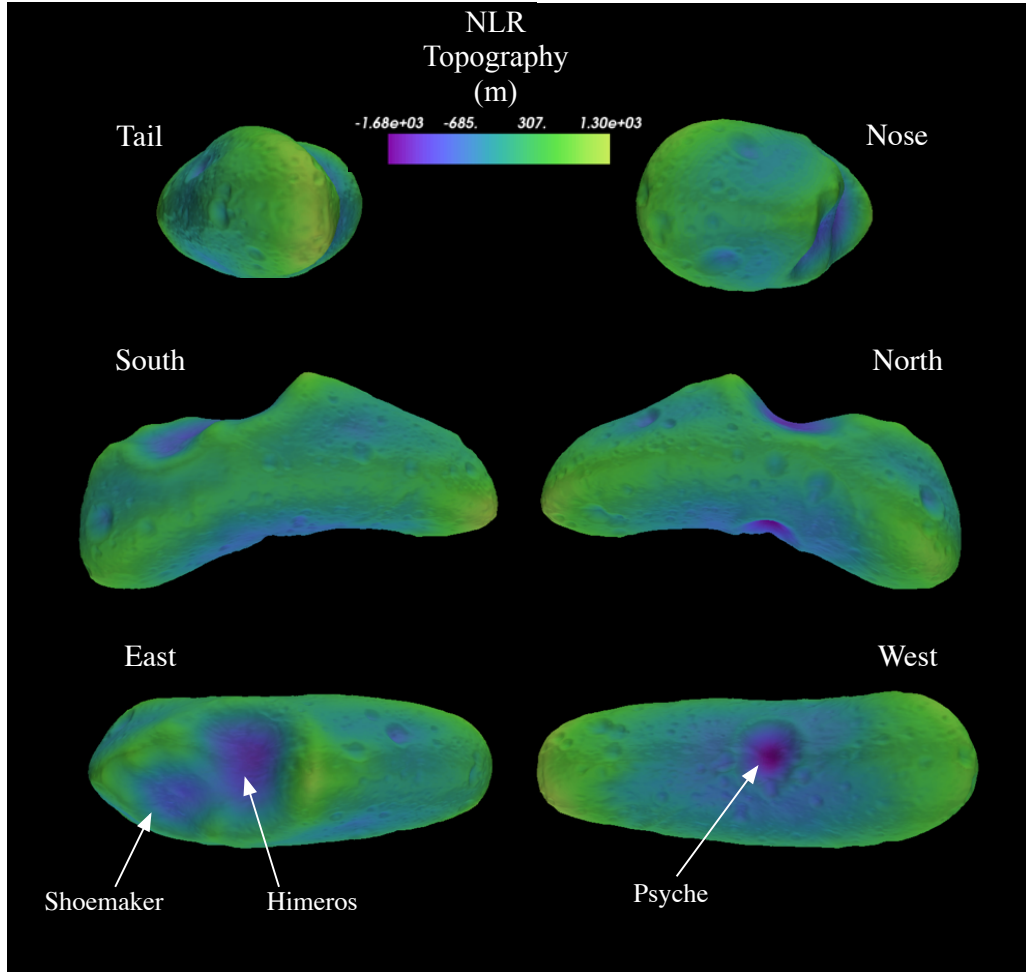


Figure 1: Topography in meters of 433 Eros derived from a shape model (Gaskell, 2008). The topography is derived from a geoid that assumes the interior of Eros is a constant density, see section 2.3 for details. The three largest craters, Himeros (10 km in diameter), Shoemaker (7.6 km in diameter, formally known as Charlios Regio), and Psyche (5.3 km in diameter) are labeled.

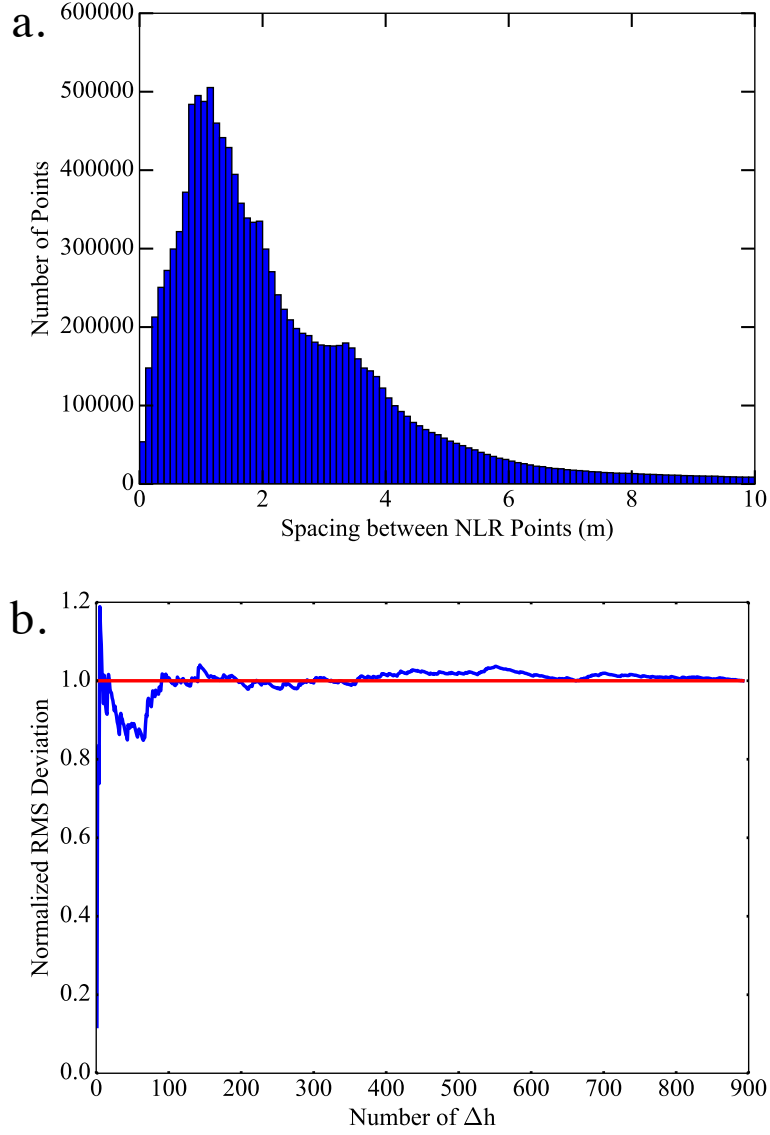


Figure 2: (a) A histogram of the direct-line spacing between NLR tracks. (b) The stability of RMS deviation $\nu(L)$ for a single location on 433 Eros at $L = 100$ m. Normalized RMS deviation is the RMS deviation for the specified number of Δh divided by the final RMS deviation for all Δh .

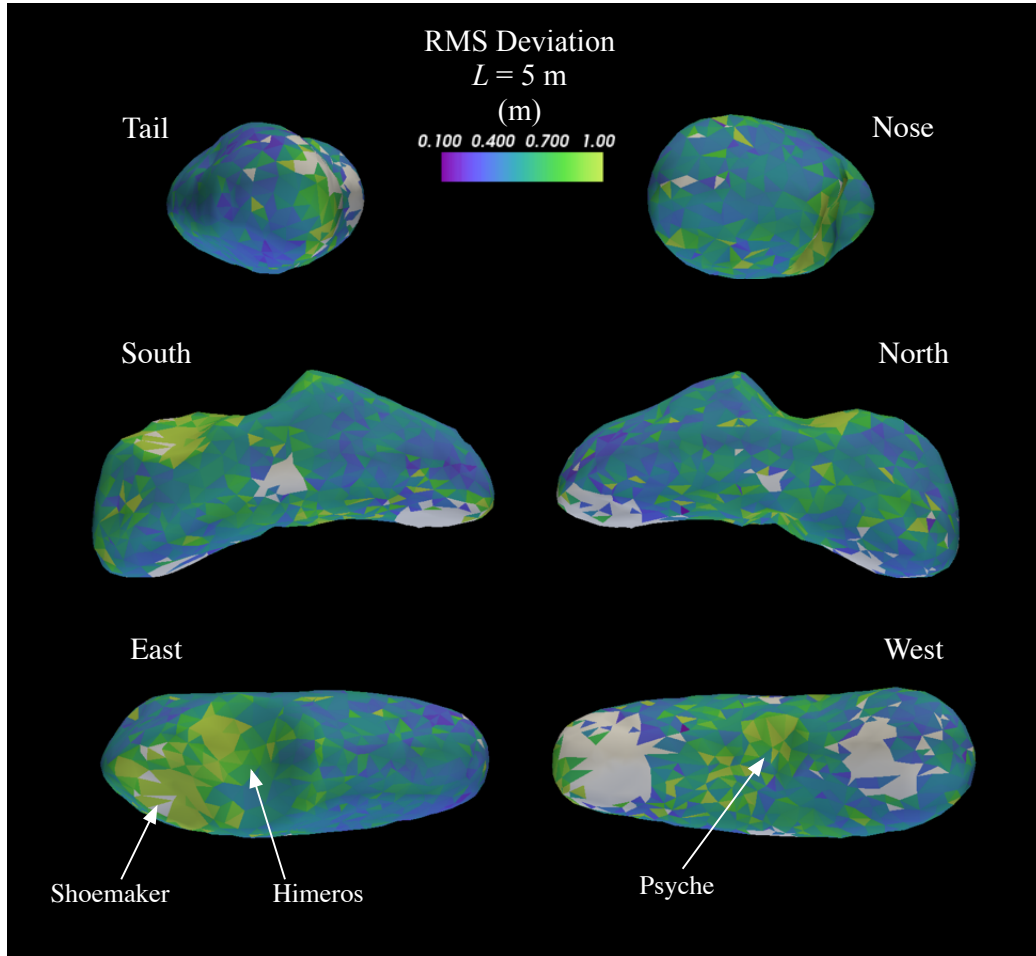


Figure 3: RMS deviation at $L = 5$ m. The surface roughness values are largest in the craters Himeros, Shoemaker, and Psyche.

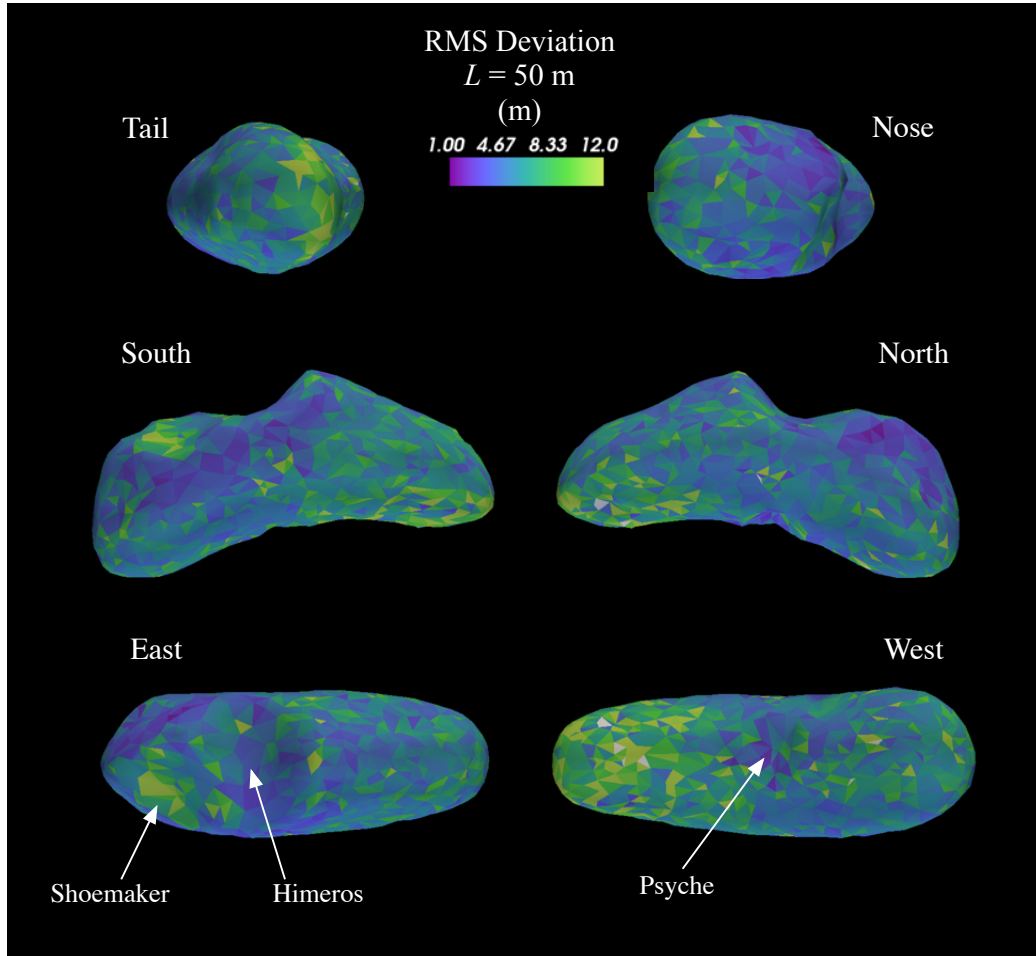


Figure 4: RMS deviation at $L = 50$ m. The surface roughness inside Shoemaker is slightly elevated compared to the surrounding region.

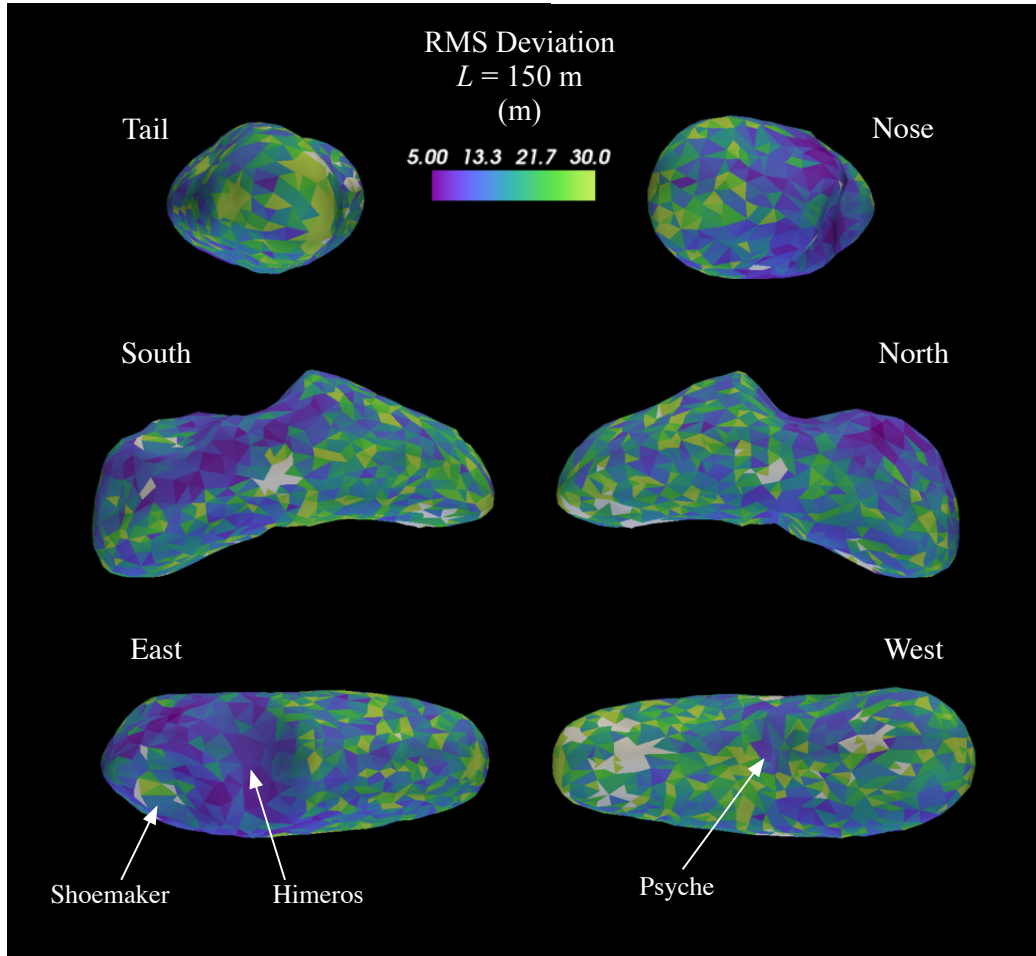


Figure 5: RMS deviation at $L = 150$ m. Low surface roughness values are found within the craters Shoemaker and Himeros.

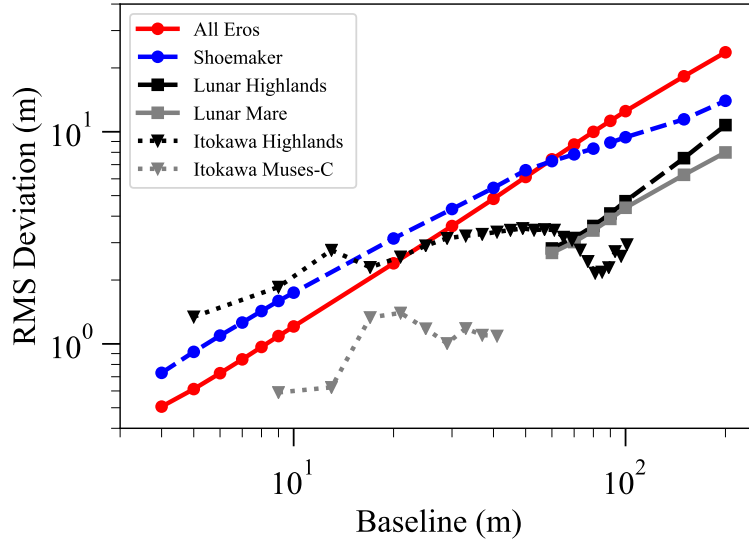


Figure 6: A devigram of 433 Eros that shows the global devigram of Eros (‘All Eros’), a devigram of Shoemaker (all surface roughness measurements within the rim of Shoemaker), a devigram of the lunar highlands, a devigram of the lunar mare, and surface roughness measurements from Itokawa’s lowlands and highlands. The devigrams of the moon were calculated by the authors for this study. The surface roughness measurements of Itokawa are from Barnouin-Jha et al. (2008).

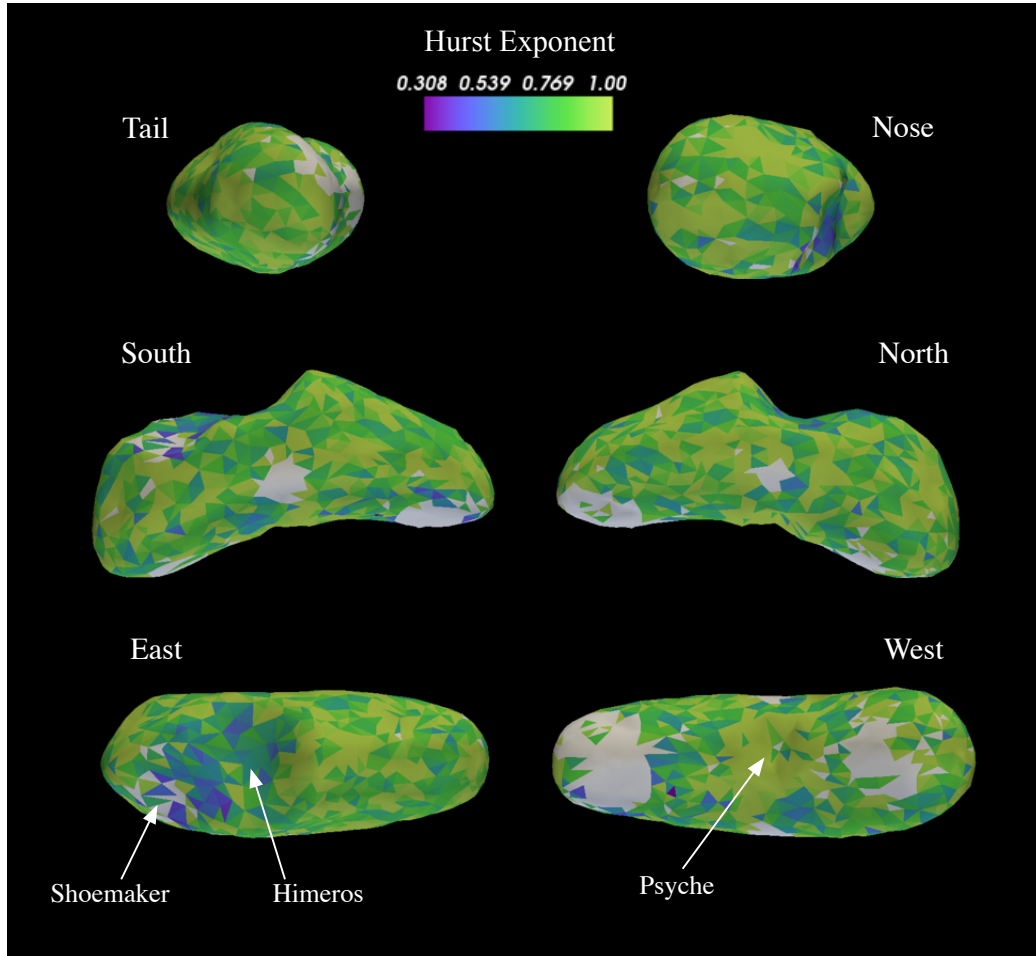


Figure 7: Map of the Hurst exponents calculated for each plate. Hurst exponents are lowest with the craters Shoemaker and Himeros and ~ 1 in Psyche.

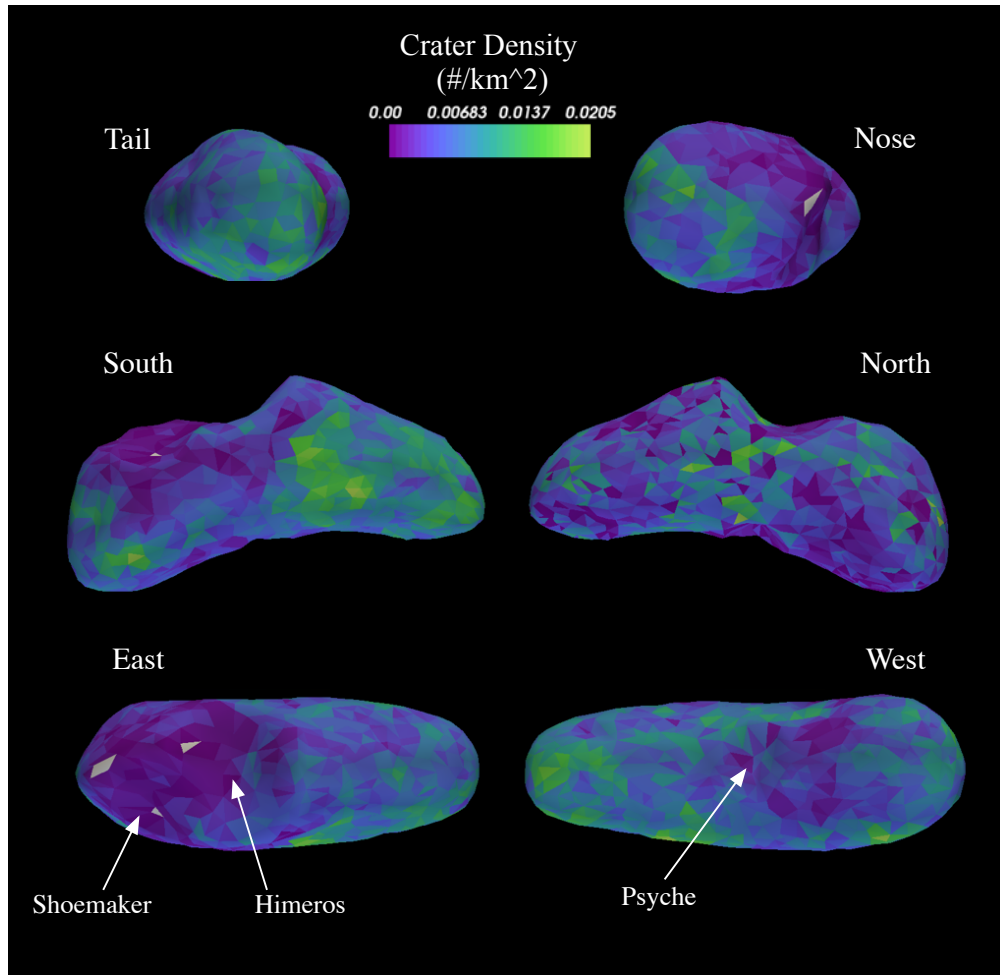


Figure 8: Crater density from Thomas and Robinson (2005). The lowest crater density is found in the craters Shoemaker and Himeros.

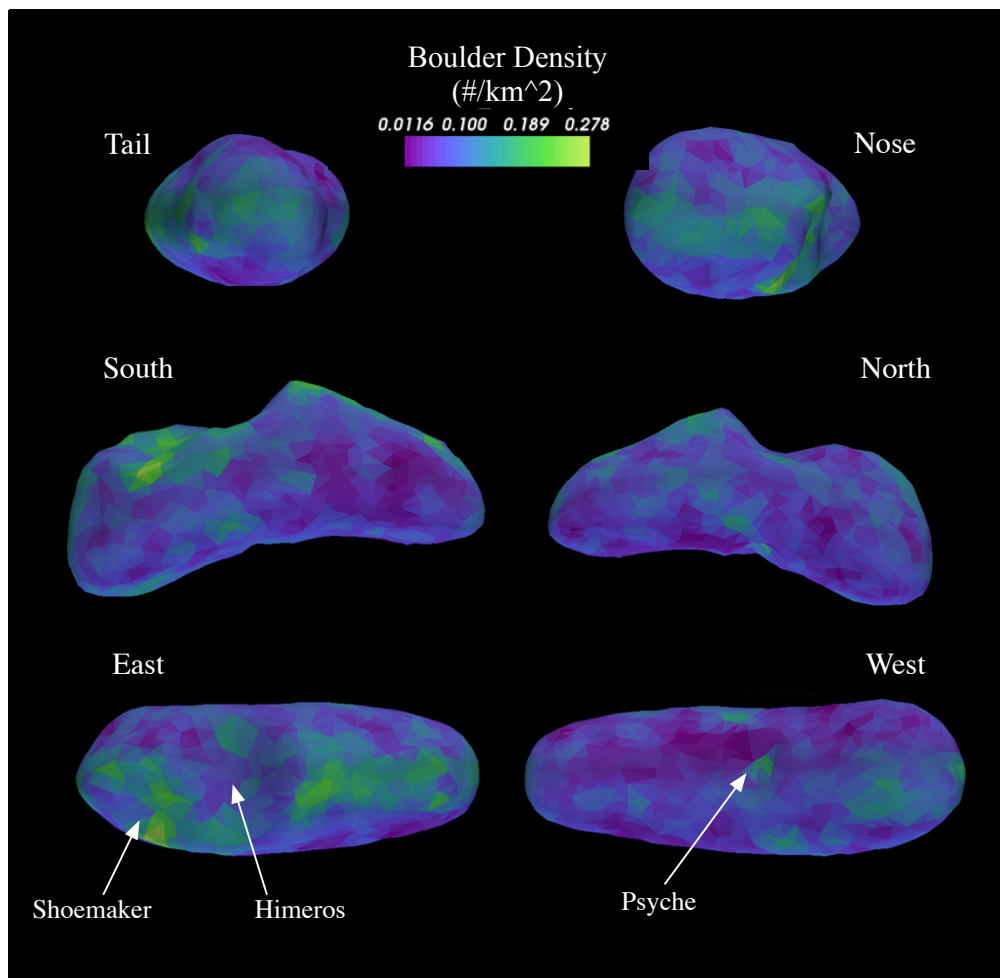


Figure 9: Boulder density from Thomas et al. (2002). The highest boulder density is in the crater Shoemaker.

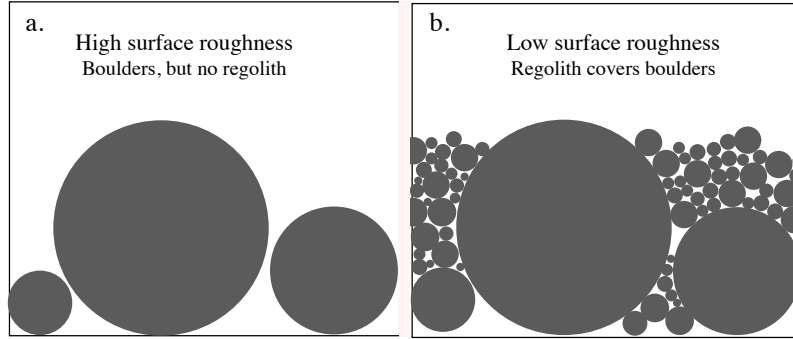


Figure 10: Schematics to show surface roughness in a boulder terrain that either (a) lacks regolith or (b) is covered by regolith.

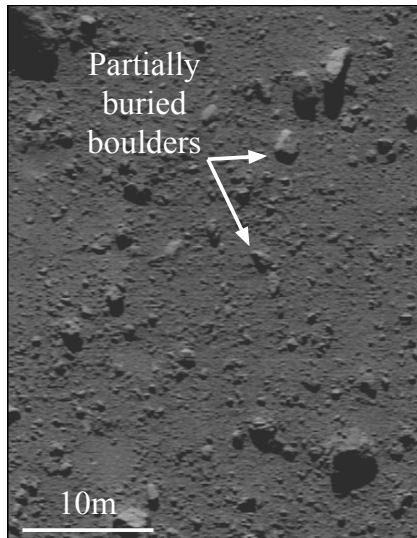


Figure 11: Image of the surface of Eros from the NEAR Multi-Spectral Imager on the southern rim of the crater Himeros. This is one of the highest resolution image of Eros (~ 0.1 m per pixel resolution). The arrows identify boulders that are buried to different degrees by regolith, similar to observations reported in Veverka et al. (2001).